The Plate Overlap Technique Applied to CCD Observations of 243 Ida

W.M. Owen, Jr., and D. K. Yeomans
Jet]'repulsion laboratory, California, Institute of 'J'ethnology

ABSTRACT

The plate overlap technique has been applied to crossing-point CCD observat ions of minor p] anet 243 Ida to produce position measurements accurate to better than 0."1 ant] measurements of position changes accurate to better than 0."06. Although these observations numbered only 17 out of the 520 that produced the final ground-based Ida ephemeris for the *Galileo* spacecraft flyby, their inclusion decreased Ida's downtrack error from 78 to 60 km and its out-of-plane error from 58 to 44 km.

1. Introduction

It has long been known that the so-called "plate overlap method" (Eichhorn 1960) produces superior star positions because forcing each star to have a unique celestial position helps to constrain the "plate constants" that transform celestial coordinates into measured coordinates. It has also been recognized (Møller & Kristensen 1966, Hemenway 1980) that observing an asteroid as it passes through the same star field at different times (a "crossing point') observat ion) can provide powerful d ifferential posit ion measurements free of star catalog error. This paper presents a set of such observations of 243 Ida obtained in April ant] May 1993, the techniques by which they were reduced, and the effect of the observations on Ida's ephemeris accuracy at the time of the Galileo spacecraft's flyby on 1993 August 28.

2. The Observations

Ida's low inclination produces very narrow retrograde loops as seem from cart]]. This property of its apparent path allows one to relax somewhat the formal definition of a crossing point: instead of requiring observations to be made near the actual spot at which the path intersects itself, one can instead observe almost anywhere within the retrograde loop provided that Ida passes through the same instrument field of view in both direct and retrograde apparent motion, In late April 1993 and again in late May 1993, Ida's path came within several arcminutes of two *Hipparcos* stars. This happy circumstance provided an excellent opportunity for crossing-point astrometry.

Observations of Ida in the same field as both *Hipparcos* stars were obtained during both April and May both at the U. S. Naval Observatory Flagstaff Station (NOFS), using the 1.55-m astrometric reflector and Tektronix 2048 x 2048 CCD camera [scale O'.'325pixel,l, field of view 11 arcminutes (Monet *et al.* 1994)], and at the Oak Ridge Obscm'story (01{0). The NOFS observations were provided to us as flattened image files, from which we extracted centroids for Ida and for several dozen field stars. The ORO observations were provided to us as a list of measured (x, y) coordinates for Ida and for stars in the "Lick Galileo Ida Reference Star Catalog" (Klemola and Owen 1992).

Table 1 presents the particulars for the observations from both sites. Owing to the varying exposure times at NOFS, the field stars were not always detectable, and occasionally the *Hipparcos* star images were saturated. Figure 1 presents the NOFS fields of view for the three nights at which observations were made there.

3. Reduction Procedures

The reductions were carried out in two steps: first each frame was reduced individually, and then the results were combined for a global reduction. Given the small field of view and the known geometric properties of CCD detectors, we decided to use a five-parameter model. The five parameters ("plate constants") for frame i were not the usual ones linear in x and y, but rather the right ascension A_i and declination D_i of the tangent point, a twist angle κ_i representing a rotation about the optical axis, and scale factors s_{x_i} and s_{y_i}. Solving for the tangent point coordinates makes the global reduction easier, especially since the telescope pointing differed significantly from night to night.

If one assumes gnomonic projection and rectangular pixels and neglects atmospheric refraction and stellar aberration, an object at right ascension α and declination δ would be imaged on the detector at rectangular coordinates (x, y) given by

$$\begin{aligned} x &= s_{x_i} P_1/P_3 + x_0 \\ y &= s_{y_i} P_2/P_3 + y_0 \end{aligned}$$

where (x_0, y_0) are the sample (column) and line (row) coordinates of the optical axis (assumed to lie at the center of the CCD), and

$$P = R_3(\kappa_i)R_1(90^\circ - D_i)R_3(A_i + 90^\circ)\begin{pmatrix}\cos\alpha\cos\delta\\ \sin\alpha\cos\delta\\ \sin\delta\end{pmatrix}$$

is the unit vector to the object measured in a coordinate system whose first and second axes lie in the CCD sample and line direction respectively. The $R_n(\theta)$ represent the usual orthogonal matrices which rotate the coordinate axes by angle θ about axis n.

Approximate values for parameters $A_i, D_i, \kappa_i, s_{x_i}$, and s_{y_i} for each frame were found from a set of individual reductions using both *Hipparcos* stars and Lick stars as reference. in turn, these parameter values allow one to calculate the approximate α and δ for any image within any frame.

The second step was a simultaneous adjustment of all frames for one observatory. The unknown parameters were the above five frame parameters for all frames and, following Eichhorn (1985), α_j and δ_j for all stars and for Ida. *A priori* values for the α_j and δ_j for uncatalogued stars were found by averaging the one-frame results. Each image of Ida was treated as a separate "star" observed but once. The coordinates of the reference stars were included in the adjustment subject to *a priori* constraints of 0″.18 for Lick stars and 0″.03 for *Hipparcos* stars. The former number was determined from the rms $O - C$ in the first step; the latter was an estimate by ESA of the accuracy of the preliminary positions provided to us. During this reduction, the effects of differential stellar aberration and differential atmospheric refraction were included to allow the corrected observations more nearly to match the ideal gnomonic projection. Measurement uncertainties for NOFS were taken directly from the centerfinding results for each image and represent the formal position uncertainties adjusted to unit weight. Measurement uncertainties for ORO *were* assumed to be 0.25 pixel based on the scatter in the star residuals from the individual reductions.

The plate overlap technique produces one position for each star which is a weighted mean of the observations including, if applicable, the input catalog position. The frame parameters are determined much better than in the first step: all star images contribute to the solution, including uncatalogued field stars if they were imaged more than once. The absolute orientation and scale of the ensemble of frames depends ultimately on the number of reference stars and on the quality of their positions. There are, however, more reference stars in the ensemble than appear on any one frame, and the uncatalogued stars strengthen the relative orientation of the frames. Consequently the absolute orientation and scale of any single frame are determined better by the plate overlap technique than by an individual frame reduction.

Uncatalogued stars that are observed only once do not contribute to the frame parameter solution since their *a priori* position is unconstrained. Rather, their measured image coordinates are effectively transformed into α and δ using the frame parameters determined by the other star images; their postfit residuals are, of necessity, zero. Retaining such stars in the plate overlap solution does not affect the quality of the solution but instead obviates the need for a follow-on program to do the transformation. The images of Ida were handled in this way.

4. Results

The positions for Ida obtained from the final reduction appear in Table 2. These are topocentric and referred to B1950 coordinates, but with the elliptic terms of aberration removed. The use of this coordinate system was required by the *Galileo* flight project. Table 2 also presents the equivalent J2000 positions, obtained following the method given by Standish *et al.* (1992); these have appeared, to lower precision, in the Minor Planet Circulars (Yeomans *et al.* 1993, McCrosky & Shao 1993).

One of the consequences of allowing the coordinates of the reference stars to be adjusted is that the coordinates for Ida become referred to a system which is a weighted mean of that defined by the two *Hipparcos* stars and that defined by the eight stars of the Lick catalog [which was reduced to the "Astrographic Catalogue Reference Stars" catalog (Corbin & Urban 1991)]. For this particular patch of sky the two systems were in close agreement: the *Hipparcos* stars moved by an average of -9 milliarcseconds (mas) in both α and δ, while the Lick stars moved by an average of +39 mas in α and +34 mas in δ. The positions for the *Hipparcos* stars are preliminary, using a subset of the *Hipparcos* observations, and not fully on the nearly inertial system of the radio stars.

Because the reference system remains uncertain at the 40-mas level, we believe that more benefit may be gained by processing these observations as differential, not absolute, measurements. Table 3 presents the NOFS results in differential form, referred to the most precise observation of that set. The position differences are given to one more digit than is customary; for the benefit of processors that cannot cope with this precision, superscript + or − signs indicate that a terminal 5 should be rounded away from or toward zero, respectively. The results for ORO do not appear in Table 3 because the differential and absolute accuracies are comparable, a result that is due, in part, to the lack of measured anonymous stars in the ORO observations.

The observations described here were included in the observation set for the final ephemeris delivered to the *Galileo* project (Yeomans *et al.* 1993), in an effort to assess Ida's ephemeris uncertainties at the time of encounter, we conducted an error analysis using the techniques outlined by Yeomans *et 01.* (1 987). The NOFS observations were assigned uncertainties of 0".1 in each coordinates, and the ORO observations 0".25, whereas the bulk of the observations were weighted at, either 0".5 or 1". Although these observations comprise but 17 of the 520 that were used to produce the final ephemeris, their high weight drove the formal uncertainty in Ida's heliocentric position at encounter from 78 x 58 x 40 km to 60 x 44 X 40 km, where the three numbers represent, in order, the downtrack, out-of-plane, and radial directions. Since these observations were made near opposition, the position uncertainty in the sun-asteroid direction was not significantly improved.

The high weight assigned to these observations is justified by the postfit residuals against a post- encounter orbit fit to 577 ground-based observations. Table 4 shows that the scatter in the residuals is consistent with the assigned weights; if anything, the NOFS observations could have been weighted more heavily. That the residual mean changed very little when the observations were fit shows that there was little bias in these observations: the system constructed by the plate overlap solution appears to be consistent with that of the other observations.

5. Conclusion

We have presented a set of crossing-point observations of 243 Ida, obtained at two different observatories in April and May 1993, reduced using the plate overlap technique. The resulting positions for Ida exhibit a very low residual scatter and are consistent with the other observations used to produce the final ephemeris for *Galileo*'s flyby of that asteroid in August 1993. The high quality of these results speaks well of the telescopes at Flagstaff and Oak Ridge and justifies the special care that was taken in the data processing. We believe that these observations are among the most accurate asteroid astrometric observations ever made.

We wish to thank the U. S. Naval Observatory Flagstaff Station and the Oak Ridge Observatory for securing the time-critical observations of Ida. Dr. Catherine Turon kindly provided preliminary positions and proper motions for the two *Hipparcos* stars.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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This preprint was prepared with the AAS LaTeX macros v3.0.

TABLE 1. observation time, exposure duration, and number of usable stars for each of the Ida crossing-point observations.

Obs. No.	Time (W C)	Exp. (s)	Number of Stars Hipp	Lick	Anon
Observations at NOFS:					
1	1993/04/28 04:35:51	G	2	7	14
2	1993/04/28 04:42:11	30	2	7	14
3	1993/04/28 04:46:22	150	2	7	14
4	1993/04/28 04:56:14	630	0	7	14
5	1993/04/29 05:41:07	24	2	3	13
G	1993/04/29 05:44:33	G	2	3	12
7	1993/04/29 05:47:48	3	2	3	13
8	1993/05/25 03:30:48	6	2	4	16
9	1993/05/25 03:33:57	30	2	4	16
10	1993/05/25 03,38:29	150	0	4	16
11	1993/05/25 03:44:10	3	2	4	16
Obs ervations at ORO:					
12	1993/04/29 01:11:49	-	2	6	0
13	1993/04/29 01:33:49	-	2	6	o
14	1993/05/26 01:48:11		2	4	0
15	1993/05/26 02 :08:04	-	2	7	0
16	1993/05/26 02: 28; 38	-	2	7	0
17	1993/05/26 02:55:36	-	2	8	0

TABLE 2. Observed astrographic positions and internal uncertainties for Ida, referred to 1119.50 coordinates with the elliptic terms of aberration removed. The rightmost two columns give the corresponding positions in the J2000 system.

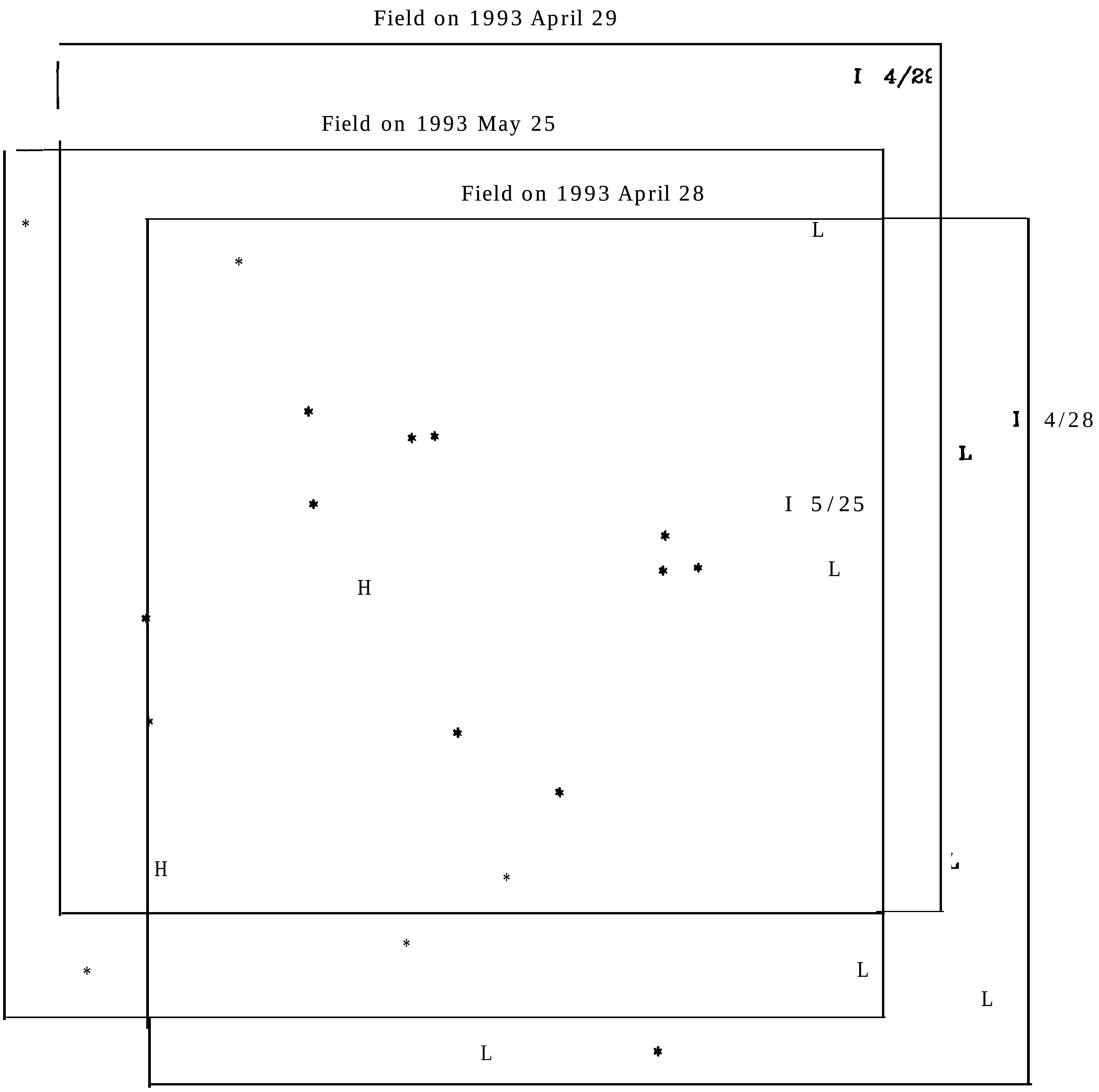
Ohs.	B1950 α	σ	B1950 δ	σ	J2000 α	J2000 δ
1	$11^{h}38^{m}45^{s}.789$	$0''.06$	+ 01005'23'!39	$0''.07$	$11^{h}41^{m}19^{s}.651$	$+00°48'45''.02$
2	$11^{h}38^{m}45^{s}.705$	$0''.06$	$+01°05'23''.91$	$0''.07$	$11^{h}41^{m}19^{s}.570$	$+00°48'45''.63$
3	$11^{h}38^{m}45^{s}.647$	$0''.06$	$+01°05'24''.28$	$0''.07$	$11^{h}41^{m}19^{s}.509$	$+00°48'46''.01$
4	$11^{h}38^{m}45^{s}.516$	$0''.06$	$+01°05'25''.07$	$0''.07$	$11^{h}41^{m}19^{s}.381$	$+00°48'46''.82$
5	$11^{h}38^{m}28^{s}.049$	$0''.08$	$+01°07'21''.83$	$0''.07$	$11^{h}41^{m}01^{s}.920$	$+00°50'43''.64$
6	$11^{h}38^{m}28^{s}.003$	$0''.08$	+ 01007'22'!11	$0''.07$	$11^{h}41^{m}01^{s}.868$	$+00°50'43''.94$
7	› $1^{h}38^{m}27^{s}.970$	$0''.08$	$+01°07'22''.41$	$0''.07$	$11^{h}41^{m}01^{s}.836$	$+00°50'44''.25$
8	$11^{h}38^{m}49^{s}.697$	$0''.05$	$+01°08'19''.47$	$0''.05$	$11^{h}41^{m}23^{s}.566$	$+00°51'41''.17$
9	$11^{h}38^{m}49^{s}.730$	$0''.04$	$+01°08'19''.27$	$0''.05$	$11^{h}41^{m}23^{s}.598$	$+00°51'40''.96$
10	$11^{h}38^{m}49^{s}.779$	$0''.04$	$+01°08'18''.95$	$0''.05$	$11^{h}41^{m}23^{s}.648$	$+00°51'40''.65$
11	$11^{h}38^{m}49^{s}.847$	$0''.05$	$+01°08'18''.56$	$0''.05$	$11^{h}41^{m}23^{s}.720$	+ 00"51 '40''.28
12	$11^{h}38^{m}31^{s}.192$	$0''.24$	$+01°07'00''.90$	$0''.24$	$11^{h}41^{m}05^{s}.060$	$+00°50'22''.72$
13	11'38W'30:911	$0''.24$	$+01°07'00''.68$	$0''.24$	$11^{h}41^{m}04^{s}.779$	$+00°50'24''.50$
14	$11^{h}39^{m}06^{s}.195$	$0''.25$	$+01°06'41''.03$	$0''.25$	$11^{h}41^{m}40^{s}.059$	$+00°50'02''.63$
15	$11^{h}39^{m}06^{s}.436$	$0''.22$	$+01°06'39''.87$	$0''.23$	$11^{h}41^{m}40^{s}.300$	$+00°50'01''.46$
16	$11^{h}39^{m}06^{s}.667$	$0''.22$	+01°06'38'!11	$0''.23$	$11^{h}41^{m}40^{s}.531$	$+00°49'59''.70$
17	$11^{h}39^{m}07^{s}.000$	$0''.22$	$+01°06'35''.47$	$0''.23$	$11^{h}41^{m}40^{s}.864$	$+00°49'57''.06$

TABLE 3. Observed positions and internal uncertainties for Ida relative to the tenth NOFS observation.

Obs.	$\Delta\alpha$	σ	$\Delta\delta$	o
1	-3?9904	$0''.046$	-1 $75''.563$	$0''.027$
2	$-4^{s}.0740$	0'!045	$-175''.045^{-}$	$0''.025$
3	$-4^{s}.1325^{+}$	$0''.021$	$-175''.671$	$0''.025$
4	$-4^{s}.2632$	$0''.028$	$-175''.877$	$0''.029$
5	$-21^{s}.7305^{+}$	$0''.054$	-57'! 121	$0''.037$
6	$-21^{s}.7761$	$0''.055$	$-57''.841$	$0''.042$
7	$-21^{s}.8095^{-}$	$0''.058$	-57'! 541	$0''.042$
8	-0?0821	0'!013	+0'!520	$0''.013$
9	$-0^{s}.0496$	$0''.009$	+0'!319	$0''.009$
10				
11	$+0^{s}.0675^{-}$	$0''.013$	$-0''.391$	0'!013

TABLE 4. Position residual statistics for the Ida observations reduced using the plate overlap technique. These residual statistics were computed using an orbital adjustment of 577 observations made from 1918 November 30 through 1993 July 1.

Fig. 1, The telescope field of view on the three nights during which NOFS observed Ida. *Hipparcos* stars, Lick stars, and anonymous field stars are marked with H, L, and *, respectively.



Field on 1993 April 29
I 4/28
Field on 1993 May 25
Field on 1993 April 28
L
I 4/28
L
I 5/25
L
H
H
L
L
L